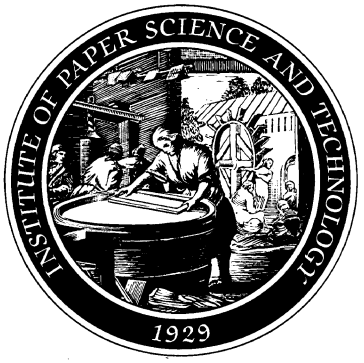

Institute of Paper Science and Technology
Atlanta, Georgia

IPST Technical Paper Series Number 658

Opening the Operating Window of Impulse Drying: II. Pressure Differential as a Source of Delamination

D.I. Orloff, T. Patterson, and P.M. Parviainen

June 1997

Submitted to
1997 TAPPI Engineering & Papermakers Conference
Nashville, Tennessee
October 6–9, 1997

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
PURPOSE AND MISSIONS

The Institute of Paper Science and Technology is a unique organization whose charitable, educational, and scientific purpose evolves from the singular relationship between the Institute and the pulp and paper industry which has existed since 1929. The purpose of the Institute is fulfilled through three missions, which are:

- to provide high quality students with a multidisciplinary graduate educational experience which is of the highest standard of excellence recognized by the national academic community and which enables them to perform to their maximum potential in a society with a technological base; and
- to sustain an international position of leadership in dynamic scientific research which is participated in by both students and faculty and which is focused on areas of significance to the pulp and paper industry; and
- to contribute to the economic and technical well-being of the nation through innovative educational, informational, and technical services.

ACCREDITATION

The Institute of Paper Science and Technology is accredited by the Commission on Colleges of the Southern Association of Colleges and Schools to award the Master of Science and Doctor of Philosophy degrees.

NOTICE AND DISCLAIMER

The Institute of Paper Science and Technology (IPST) has provided a high standard of professional service and has put forth its best efforts within the time and funds available for this project. The information and conclusions are advisory and are intended only for internal use by any company who may receive this report. Each company must decide for itself the best approach to solving any problems it may have and how, or whether, this reported information should be considered in its approach.

IPST does not recommend particular products, procedures, materials, or service. These are included only in the interest of completeness within a laboratory context and budgetary constraint. Actual products, procedures, materials, and services used may differ and are peculiar to the operations of each company.

In no event shall IPST or its employees and agents have any obligation or liability for damages including, but not limited to, consequential damages arising out of or in connection with any company's use of or inability to use the reported information. IPST provides no warranty or guaranty of results.

OPENING THE OPERATING WINDOW OF IMPULSE DRYING: II. PRESSURE DIFFERENTIAL AS A SOURCE OF DELAMINATION

D.I. Orloff
Professor and Director
Engineering Division
Institute of Paper Science and Technology
Atlanta, GA 30318
USA

T. Patterson
Senior Associate Engineer
Engineering Division
Institute of Paper Science and Technology
Atlanta, GA 30318
USA

P.M. Parviainen
Graduate Student
Institute of Paper Science and Technology
Atlanta, GA 30318
USA

ABSTRACT

In recent experiments by Krause,[1,2] sheets exposed to elevated ambient pressures at nip opening were free of delamination. It was proposed that these elevated ambient pressures reduced the pressure difference across the sheet and thereby eliminated the imbalanced forces that cause delamination.

In this work, high ambient pressure impulse drying (HAPID) experiments were conducted with thermocouple-containing handsheets to allow the measurement of internal sheet temperatures. The temperature data were used to deduce pressure differences between the inside and outside of the sheets and to relate these to delamination. The results support the view that delamination occurs when the pressure difference across the sheet is too high, and the buildup of internal pressure bursts the sheet.

LITERATURE REVIEW

Delamination is believed to be caused by high temperature, high pressure, water in the sheet that is suddenly exposed to a low pressure environment as the nip is opened. This results in a large pressure difference between the inside and outside of the sheet as well as production of vapor that cannot readily escape the sheet. As a consequence, the sheet blisters.

Recent experiments at IPST have shown that exposing the sheet to elevated ambient pressures as the nip is opened effectively inhibits delamination.[1] Gaining additional information about the pressure and temperature inside the sheet would be very beneficial in further clarifying the mechanism by which elevated ambient pressure inhibits delamination.

HYPOTHESIS

The purpose of this study was to measure the temperature distribution within layers of impulse dried sheets at both elevated and ambient pressures. Using these data and thermodynamic reasoning, pressure profiles were determined within the web. Based on these profiles, the hypothesis that delamination was caused by an inbalance of internal and external sheet pressure was tested.

EXPERIMENTAL

There were two parts to the experimental plan of this study:

1) Determine the elevated ambient pressure required to inhibit delamination at selected platen temperatures.

2) Once these "critical ambient pressures" were determined, similar but layered handsheets were prepared with embedded thermocouples to allow the measurement of z-direction temperature profiles as the layered sheets were impulse dried.

Determination Of Critical Pressure

Critical ambient pressure is the minimum pressure that is needed to inhibit delamination, all other conditions being held constant. As a baseline, 10 identical experiments were conducted at each of four platen temperatures with the nip opening to one atmosphere pressure to demonstrate that delamination occurs. In the next sequence of experiments, the ambient pressure at nip opening was raised until delamination was inhibited. A minimum of at least 30 experiments at elevated ambient pressures was conducted at each platen temperature to accurately determine the "critical ambient pressure." Z-direction ultrasonic testing and visual examination were used to determine the extent of delamination. The elevated ambient pressure was measured using a pressure transducer located inside the pressurized impulse drying chamber. Basis weight, water removal, and felt weights were collected for each of these experiments.

Determination Of Internal Temperature Profiles

Once the "critical ambient pressures" were determined, sheets with embedded thermocouples were prepared. A minimum of at least 10 identical experiments was conducted at each platen temperature. At least five experiments were conducted at one atmospheric ambient pressure and then at least five more experiments at ambient pressures at-or-above the "critical ambient pressure." The thermocouples were embedded in four different regions of the sheet. The thermocouples were used to measure internal temperature every 0.25 ms throughout the entire impulse drying event. Based on previous work,[1] the response time of the 0.05-mm diameter thermocouples was adequate for these experiments. The objective was to determine the effect of delamination and ambient pressure on temperature profiles within the sheet. The data would then be used to determine the internal pressures within the sheet.

Experimental Procedures

The details of the apparatus and procedures used in this work are given in Parviainen,[3] and were generally similar to those used by Krause.[1,2] However, as some additional measurements were made during these experiments, the equipment and procedures involving those measurements are herein described.

Furnish.

A furnish and grade were chosen that would be commercially important for impulse drying. A commercially produced 100% virgin softwood kraft linerboard pulp was selected.

Commercially produced kraft linerboard pulp was received at 15% consistency. The pulp was then refined in a 4.54-kg valley beater. The pulp was refined to 398 ml CSF. It was then washed and dewatered in a centrifugal washer to 10%C. The pulp was then refrigerated and stored at 4°C until later use.

Single-Ply Handsheets.

Single-ply handsheets, to be used in determining critical ambient pressure, were made to a target basis weight of 205 g/m^2. These were produced in a British handsheet mold according to the procedures outlined in TAPPI T205 om-88. The pulp was disintegrated at 0.25%C for 15,000 revolutions. The sheets were formed from the 0.25%C stock and were pressed to a target of 35% solids using a manually applied hydraulic press. As a control, one out of every 10 sheets was oven dried and weighed to ensure correct basis weight. The pressing was done at 929 kPa for 10 seconds with three blotters on top and one blotter on the bottom side. The samples were cut with a 6.35-cm diameter knife edged die in a THWING-ALBERT Alfa cutter model 240-3. Each sheet was formed, labeled, and pressed to 35% solids and then individually placed in sealed plastic bags. The individually bagged samples were stored at 4.4°C until needed.

Thermocouple Instrumented Handsheets.

In order to measure internal sheet temperature profiles during impulse drying, multilayer handsheets were produced with imbedded thermocouples. A four-layered sheet containing three imbedded thermocouples was utilized. The top layer was made as thin as possible to allow temperature measurement close to the heated surface of the sheet, while being thick enough to eliminate the possiblity of it electrically shorting to the surface of the heated platen. The basis weight for the top layer was 20 g/m^2. The second and third layers were each 50 g/m^2, while the bottom, or fouth layer, was 85 g/m^2. The individual layers were formed on the handsheet mold and then couched off the wire. For the light top layer, it was necessary to wet the blotter to ensure good couching.

Sample mounting rings were made to affix the thermocouples and allow for easy transfer and storage of assembled sheets. The mounting rings are 0.32-cm thick annular cardboard rings with a 10.2-cm outer diameter and with approximately a 8.9-cm inner diameter. Three type E 0.051-mm diameter thermocouples were mounted onto the mounting rings, which were then placed on the surface of the manual handsheet press. The mounting rings were weighed separately so that the percent solids of the formed sheet could accurately be determined and adjusted. Each layer was then assembled with the appropriate thermocouple between the layers. When all the layers with their respective thermocouples had been made, four blotter sheets were placed on the top and bottom sides of the sample and pressed at 515 kPa for 7 seconds. The bottom thermocouple was not placed on the mounting ring because it was more practical to mount the bottom thermocouple permanently onto the sheet lifter located above the lower platen. To conduct the tests, the mounting ring with sample were clamped to the sheet lifter above the lower pressing surface. The thermocouple leads were then connected to the female plugs located below the lower platen.

Thermocouples.

Type E 0.051-mm diameter thermocouples were used to obtain the internal sheet temperatures. They were made with an approximate 6.3-cm loop, which would go inside the sheet. It was important to ensure that the leads did not cross in order to achieve an accurate temperature reading. The wires were insulated with approximately 10-cm long Teflon leads. The sheathed wires were connected to a type E male plug, which

was plugged into the female connector located below the pressing surface on the lower platen.

RESULTS

Determination Of Critical Pressure

The first part of the experimental study was to determine for the furnish used and for a range of platen surface temperatures, the minimum ambient chamber pressures required to inhibit delamination. The platen temperatures chosen were 130, 200, 230, and 260°C. The ambient pressure at nip opening was systematically increased from atmospheric pressure up to 750 kPa (abs), depending on the platen temperature. The highest pressures were chosen to examine if extremely high ambient pressure has an effect on sheet properties.

To determine "critical ambient pressure," a set of 10 sheets was impulse dryed at a given temperature and then examined visually and with ultrasound to determine if delamination had occurred. The ultrasonic testing was conducted at five different regions of the sheet, four on the outer edges and one in the center. It records the velocity of sound, or square root of the specific elastic modulus, in the out-of-plane direction of the sheet. As in previous studies, the coefficient of variation of the specific elastic modulus proved useful in detecting delamination. The details of these measurements are given in Parvianen.[3] The critical pressures corresponding to the platen temperatures of 200, 230, and 260°C were 220, 290, and 295 kPa (abs), respectively.

Water Removal

The samples impulse dryed in this part of the study were also tested for moisture removal, with the detailed results reported in Parvianen.[3] The data showed that neither delamination nor ambient pressure had an effect on water removal. The general trend was that moisture removal increased with increased platen temperature as had been previously reported.

Internal Sheet Temperature Profiles

After the critical ambient pressures had been determined, replicate experiments using thermocouple instrumented handsheets were impulse dryed. The top thermocouple, designated T_{TOP}, was placed below the thin top layer representing about 10% of the total sheet weight. The second thermocouple, designated $T_{1/4}$, was placed below about 35% of the total sheet weight. The third thermocouple, designated $T_{1/2}$, was placed below about 60% of the total weight of the sheet. The fourth thermocouple, designated T_{BOTTOM}, was placed just below the bottom of the sheet, and in contact with the felt, the farthest away from the heated platen. Figures 1 and 2 show typical internal temperature profiles for the 260°C platen surface temperature case where ambient pressure was set at 101 and 320 kPa, respectively.

A minimum of five replicate experiments was conducted at each platen temperature at both an ambient pressure of one atmosphere and at the corresponding critical ambient pressure.

ANALYSIS

The internal sheet temperature profiles all contain an increase in temperature while the press load is being applied. As the nip begins to open, the profiles also show a further rapid increase in temperature followed by a rapid decrease in temperature as the press load approaches the ambient pressure. In the region where the temperature is rising under a heavy load, the water inside the sheet is a subcooled liquid. As soon as the load is decreased, heat transfer along with the pressure drop cause the subcooled liquid to first increase in temperature (until it reaches saturation conditions) and then to begin to vaporize. As the phase change begins, vapor produced begins to escape from the interior of the sheet. The combined effect of sheet expansion and vapor venting controls the rate of pressure drop within the sheet. By increasing the external load (increasing the ambient pressure) during this period, we are also reducing the pressure difference between the inside and outside of the sheet.

As shown in the Appendix, the rate of temperature change with respect to time is determined by the rate of pressure drop as well as the rate of heat transfer to a subcooled liquid. Heat transfer to the system will tend to increase system temperature, while a system pressure drop will also tend to increase the system temperature. However, as soon as the system becomes saturated, the temperature change will reflect the change in pressure through the vapor pressure curve.

$$\frac{dT}{dt} = \frac{\left\{\frac{1}{m}\right\}\frac{\delta Q}{dt} - \left\{\left(\frac{\partial u}{\partial P}\right)_T + P\left(\frac{\partial v}{\partial P}\right)_T\right\}\frac{dP}{dt}}{\left\{\left(\frac{\partial u}{\partial T}\right)_P + P\left(\frac{\partial v}{\partial T}\right)_P\right\}}$$

To show this graphically, this calculation has been made at fixed temperatures of 150 and 250°C as shown in Figures 3 and 4.

It is observed that a substantial drop in system temperature can only be expected to occur if the system is saturated, i.e., vaporization has commenced.

Hence, one can estimate the instant when a particular location within the sheet reaches saturation conditions. In fact, we can use the instant when the internal temperature rapidly drops as the start of saturation conditions. Once vaporization begins, the local pressures within the sheet correspond to the local saturation pressures at the measured local internal temperatures. The pressures in KPa are then calculated from the measured temperatures in °C and the vapor pressure curve.

Typical internal pressures and the load pressure transmitted to the sheet are plotted as a function of time for the 260°C platen temperature case at ambient pressures of 101 and 320 kPa (abs) in Figures 5 and 6.

Assuming that we know the external pressure applied to the sheet, the pressure differential between the inside and outside of the sheet can then be determined.

The External Pressure Applied To The Sheet

During impulse drying under elevated ambient chamber pressure, the sheet experiences a number of different forces. The force on the sheet that is applied as the load is increasing is just the load as measured by the load cell mounted on the shaft of the upper platen. However, as soon as the ambient pressure begins rising in the chamber, the actual load applied to the sheet is less than that registered on the load cell. This is because the pressurized nitrogen inside the chamber applies an upward force onto the annular region on the upper surface, outside of the upper platen and lower platen contact area.

This region is about $(10.47 \text{ cm} - 6.35 \text{ cm})^2 * \Pi/4$ in area. So, the net force applied to the sheet is

$$\text{Psheet} = ((\text{Pressure on Load Cell} * \text{Area of sheet}) - \text{Pchamber} *((10.47 - 6.35)^2 * (\Pi/4))/(\text{Area of sheet})$$

The equation for Psheet is only applicable when the upper platen and lower platen are in contact. As soon as the two platens separate, the load cell registers a constant load, which is just the area of the piston multiplied times the chamber pressure (Pchamber). The fact that the load is constant at this point indicates that the two platens are separated and the elevated chamber pressure acts on the entire surface, and not only the annular region. Using this reasoning, the time at which the two platens first separate can be determined. It was then assumed that for the atmospheric cases, the upper and lower platen separate at that same moment in time as for the pressurized case. After the nip has opened, the pressure on the sheet is just the chamber pressure (Pchamber). The combination of all of these events can be used to determine exactly what the external pressure on the sheet is during the entire pressing cycle, as shown in Figures 5 and 6.

Using the determined pressure on the sheet, designated as Psheet in the graph, the pressure differential between the internal and external regions of the sheet was calculated. Typical pressure differential results are plotted in Figures 7 and 8 for the 260°C platen temperature case at both 101 and 320 kPa (abs) ambient pressure.

Similar plots were constructed for all cases, and the peak pressure drop was determined for each case. We anticipate that the instant of peak pressure drop is the most likely time at which delamination occurs. It appears that the reason why elevated ambient pressure inhibits delamination is because it decreases the maximum pressure drop. This is evident from Figure 9 where the maximum pressure differential at the "1/4" location is plotted as a function of platen surface temperature. It is observed that the maximum pressure differential increased linearly with platen surface temperature and decreased with increasing ambient pressure at nip opening. Recall that the cases at an ambient pressure of 101 kPa delaminated, while those at ambient pressures above the critical pressures did not delaminate.

To demonstrate that it is the increase in ambient pressure, and not a reduction in the internal pressure that eliminated delamination, we plot the peak internal sheet temperature as a function of platen temperature as shown in Figure 10. We observe that the peak internal temperature at position "1/4" was independent of ambient pressure. As the internal pressure is directly related to the internal temperature, raising the ambient pressure at nip opening had no influence on the peak internal pressure.

Note that sheets impulse dryed at an ambient pressure of 101 kPa (abs) at a platen temperature of 200°C delaminated, while similar sheets impulse dryed at an ambient pressure of 320 kPa (abs) at a platen temperature of 260°C did not delaminate. From Figure 9, we then conclude that delamination must occur at the "1/4" location in the sheet when the peak pressure differential exceeds about 225 kPa.

CONCLUSIONS

Samples of 205 g/m^2 100% virgin kraft linerboard refined to 398 ml CSF were impulse dried using platen temperatures of 200, 230, and 260°C. At atmospheric conditions, delamination was always present. Exposing the sheet to elevated ambient pressure upon opening the nip inhibited delamination. This is because the fiber network can withstand the lower pressure differentials experienced during elevated

ambient pressure impulse drying, but not those experienced during conventional impulse drying.

The experiments conducted in this study indicate that there was a maximum threshold pressure difference between the internal and external pressure of the sheet above which delamination will occur. In this case, the maximum allowable pressure drop between the "1/4" layer of the sheet and the surface was about 225 kPa. Pressure differences greater than 225 kPa always caused delamination.

APPENDIX - A THERMODYNAMIC INTERPRETATION OF THE NIP OPENING PROCESS

Recent Institute research has shown that changes in the nip opening process can significantly impact sheet delamination during impulse drying. In order to better understand the nip opening process, a thermodynamic model was developed.

A CONCEPTUAL VIEW

In this Appendix, the nip opening process is viewed as a series of thermodynamic processes that are experienced by the sheet. Figure 11 shows a conceptual view of the out-of-plane moisture, pressure, and temperature profiles in a sheet that is undergoing impulse drying at an instant of time just prior to the start of nip opening. The top surface of the sheet is in contact with the heated press roll, which acts as a heat source, while the bottom surface of the sheet is in contact with the press felt, which acts as a water reservoir. Sheet moisture is at its lowest value at the sheet-roll interface and at its highest value at the sheet-felt interface. Sheet temperature is at its maximum at the sheet-roll interface and at its minimum value at the sheet-felt interface.

There are three distinct regions of the sheet. In Region **a**, near the press roll surface, the pores of the sheet contain little water and are at high temperature. In Region **b**, in the middle of the sheet, the pores contain liquid water and are at moderately high temperatures (more than 100°C). In Region **c**, near the press felt, the pores contain substantial water and are at a low temperature (less than 100°C). In this conceptual model, only the pores in Region **b** of the sheet contain enough water and are at sufficiently high temperature for flashing to vapor to occur as the nip opens.

As the nip opens, the applied pressure decreases until the heated surface of the sheet is no longer in contact with the heated press roll. During this time interval, the heated press roll continues to transfer heat to the sheet and to the pores. This combination of pressure drop and heat transfer results in rapid flash evaporation of the liquid contained in the pores of Region **b**, and in evaporative cooling.

It has been previously proposed that sheet delamination is the result of the flash evaporation process. If the sheet above region **b** were assumed (in the extreme case) to be impermeable, flashing in the pores would result in sheet expansion. In the more realistic case, where the sheet above region **b** is permeable, flashing in the pores will result in both venting of flashed vapor, to the sheet-platen interface, and sheet expansion. In both cases, interfiber bond failure will occur when the net forces on the sheet, above region **b**, exceed the failure strength of region **b**.

It is here proposed that the probability of delamination can be reduced by modifying the nip opening process to reduce the net forces on the sheet. The intent of the following model is to begin to develop an understanding of the variables that would be expected to influence the process. The model represents a limiting case in that it assumes that the web is impermeable above region **b**, and, hence, that there is no venting.

THERMODYNAMIC MODEL

Consider a pore in Region **b** of the sheet. The mass of water contained within that pore may be defined as a thermodynamic system. As the sheet is expected to increase in caliper as the nip opens, the boundaries of the thermodynamic system (pore) expand when the water within undergoes a change of phase. Figure 12 shows the thermodynamic system at the beginning of the process and at some later time during the process.

In Figure 12, and in the following derivation,

m	=	the system mass (water)
Q	=	the heat transfer to the system from the surroundings
W	=	the work done by the system on the surroundings

The following assumptions are introduced:

1. The mass of the system is conserved. There is no water vapor venting or transfer of liquid water during depressurization of the sheet.

2. The surface of the system expands with time, doing reversible work on the surroundings.

3. Heat is transferred from the surroundings to the system.

4. The pressure of the system depends on its z-directional location in the sheet, the decreasing applied load, and various initial conditions.

At the beginning of depressurization, the thermodynamic system is at a pressure, P_{max}, and at a temperature, T_{max}. It is anticipated that P_{max} may be higher than the saturation pressure, P_{sat}, corresponding to the temperature, T_{max}. Hence, at the onset of depressurization, the system may be a subcooled liquid. In such a case, depressurization will proceed until the system becomes a saturated liquid. From that point on, continued depressurization results in vaporization with a subsequent substantial increase in volume. As a special case, P_{max} may be equal to P_{sat} so that the system starts off as a saturated liquid and vaporization proceeds immediately with depressurization.

If the starting pressure, P_{max}, were less than P_{sat}, then no vaporization would take place as the system would already be a superheated vapor. In that case, vaporization would take place in a pore that is located farther away from the heated surface of the sheet at the saturation temperature, T_{sat}, corresponding to the starting pressure, P_{max}.

Figure 13 shows the process on a T-v diagram. It is observed that the process may be separated into two regimes, a subcooled liquid regime, where the system volume increases slightly with a reduction in system pressure, and a saturated regime, where a system pressure decrease results in vaporization and a large increase in system volume.

THE SUBCOOLED REGIME

In the subcooled regime, the specific volume of the system, v, is a function of both system temperature, T, and system pressure, P.

$$v = v(P,T) \qquad \{1\}$$

Hence, changes in pressure and temperature will result in a change in the specific volume.

$$dv = \left(\frac{\partial v}{\partial P}\right)_T dP + \left(\frac{\partial v}{\partial T}\right)_P dT \qquad \{2\}$$

As the mass of the thermodynamic system, m, is constant with respect to time, the rate of system volume increase can be written as

$$\frac{dV}{dt} = m\frac{dv}{dt} \qquad \{3\}$$

Substituting {2} into {3} yields

$$\frac{dV}{dt} = m\left(\left(\frac{\partial v}{\partial P}\right)_T \frac{dP}{dt} + \left(\frac{\partial v}{\partial T}\right)_P \frac{dT}{dt}\right) \qquad \{4\}$$

From the first law of thermodynamics, the heat transfer to the system must equal the sum of the change in internal energy of the system and the work done by the system on its surroundings.

$$\frac{\delta Q}{dt} = \frac{dU}{dt} + \frac{\delta W}{dt} \qquad \{5\}$$

The internal energy of the system is

$$U = mu \qquad \{6\}$$

Hence, the rate of increase in the system internal energy is

$$\frac{dU}{dt} = m\frac{du}{dt} = m\left[\left(\frac{\partial u}{\partial P}\right)_T \frac{dP}{dt} + \left(\frac{\partial u}{\partial T}\right)_P \frac{dT}{dt}\right] \qquad \{7\}$$

The reversible work done by the system on the surroundings is

$$\frac{\delta W}{dt} = P\frac{dV}{dt} \qquad \{8\}$$

Substituting {4} into {8} yields

$$\frac{dW}{dt} = Pm\left[\left(\frac{\partial v}{\partial P}\right)_T \frac{dP}{dt} + \left(\frac{\partial v}{\partial T}\right)_P \frac{dT}{dt}\right] \qquad \{9\}$$

Combining {9} and {7} into {5} results in

SEE OVERSIZED EQUATIONS {10}

Solving for the rate of change of temperature

$$\frac{dT}{dt} = \frac{\left\{\frac{1}{m}\right\}\frac{\delta Q}{dt} - \left\{\left(\frac{\partial u}{\partial P}\right)_T + P\left(\frac{\partial v}{\partial P}\right)_T\right\}\frac{dP}{dt}}{\left\{\left(\frac{\partial u}{\partial T}\right)_P + P\left(\frac{\partial v}{\partial T}\right)_P\right\}} \quad \{11\}$$

We may now substitute {11} into {4} to obtain the increase in the volume of the system.

THE SATURATED REGIME

In the saturated regime, the mass of liquid water, m_L, may decrease with time, and the mass of water vapor, m_V, may increase with time. Yet, the total mass of water, contained within the system boundaries, must remain constant. Hence, from continuity,

$$m = m_L + m_V = CONSTANT \quad \{12\}$$

Differentiating with respect to time,

$$\frac{dm}{dt} = \frac{dm_L}{dt} + \frac{dm_V}{dt} = 0 \quad \{13\}$$

Hence, the rate of loss of liquid water, m_L, is equal and opposite in sign to the rate of increase of water vapor, m_V.

$$\frac{dm_L}{dt} = -\frac{dm_V}{dt} \quad \{14\}$$

The system volume may be calculated from the volume of the liquid water and water vapor contained within the system boundaries.

$$V = m_L v_f + m_V v_g \quad \{15\}$$

Differentiating with respect to time,

$$\frac{dV}{dt} = m_L\frac{dv_f}{dt} + v_f\frac{dm_L}{dt} + m_V\frac{dv_g}{dt} + v_g\frac{dm_V}{dt} \quad \{16\}$$

The rate of increase in the system volume can be simplified by recognizing that v_f and v_g are both only functions of pressure, (note: $v_{fg} = v_g - v_f$) and by using {14},

$$\frac{dV}{dt} = v_{fg}\frac{dm_V}{dt} + \frac{dP}{dt}\left[(m - m_V)\frac{dv_f}{dP} + m_V\frac{dv_g}{dP}\right] \quad \{17\}$$

Where $\frac{dP}{dt}$ is the rate of change of the system pressure.

Again, from the first law of thermodynamics,

$$\frac{\delta Q}{dt} = \frac{dU}{dt} + \frac{\delta W}{dt} \quad \{18\}$$

Where the system internal energy, U, is given by

$$U = m_L u_f + m_V u_g \quad \{19\}$$

Noting that, $u_{fg} = u_g - u_f$, we may write the rate of change of the system internal energy as

$$\frac{dU}{dt} = u_{fg}\frac{dm_V}{dt} + \frac{dP}{dt}\left[m\frac{du_f}{dP} + m_V\frac{du_{fg}}{dP}\right] \quad \{20\}$$

As all of the work done by the system is boundary expansion work,

$$\delta W = PdV \quad \{21\}$$

Hence,

$$\frac{\delta W}{dt} = P\frac{dV}{dt} \quad \{22\}$$

Substituting {17} into {22} yields

$$\frac{dW}{dt} = v_{fg}P\frac{dm_V}{dt} + P\frac{dP}{dt}\left[m\frac{dv_f}{dP} + m_V\frac{dv_{fg}}{dP}\right] \quad \{23\}$$

Combining {23}, {20}, and {18}, we may solve for the evaporation rate

SEE OVERSIZE EQUATIONS {24}

Knowing the initial thermodynamic state of the system and the rate of change of the system pressure and the rate of heat transfer, as imposed by the surroundings, we may use {24} and {12} to predict the water vapor contained in the system as a function of time.

REFERENCES

1. Krause, A; The Effect of Ambient Pressure on Sheet Delamination in Impulse Drying. M.S. Thesis, IPST, 1995.

2. Orloff, D. I.; Patterson, T.; Krause, A.M. "Opening the Operating Window of Impulse Drying - I. The Effect of Ambient Pressure at Nip Opening," 1997 TAPPI Engineering and Papermakers Conference, October 6-9, 1997, Nashville, TN.

3. Parviainen, P.M.; Internal Web Temperature Profiles During High Ambient Pressure Impulse Drying. M.S. Thesis, IPST, 1996.

ACKNOWLEDGEMENT

The authors would like to thank the Member Companies of the Institute of Paper Science and Technology for supporting this research. Portions of this work were used by P.M.P. as partial fulfillment of the requirements for the M.S. degree at the Institute of Paper Science and Technology.

OVERSIZE EQUATIONS

$$\frac{\delta Q}{dt} = m\left\{\left[\left(\frac{\partial u}{\partial P}\right)_T + P\left(\frac{\partial v}{\partial P}\right)_T\right]\frac{dP}{dt} + \left[\left(\frac{\partial u}{\partial T}\right)_P + P\left(\frac{\partial v}{\partial T}\right)_P\right]\frac{dT}{dt}\right\} \quad \{10\}$$

$$\frac{dm_V}{dt} = \frac{\frac{\delta Q}{dt} - \frac{dP}{dt}\left[m\left(\frac{du_f}{dP} + P\frac{dv_f}{dP}\right) + m_V\left(\frac{du_{fg}}{dP} + P\frac{dv_{fg}}{dP}\right)\right]}{u_{fg} + v_{fg}P} \quad \{24\}$$

ILLUSTRATIONS

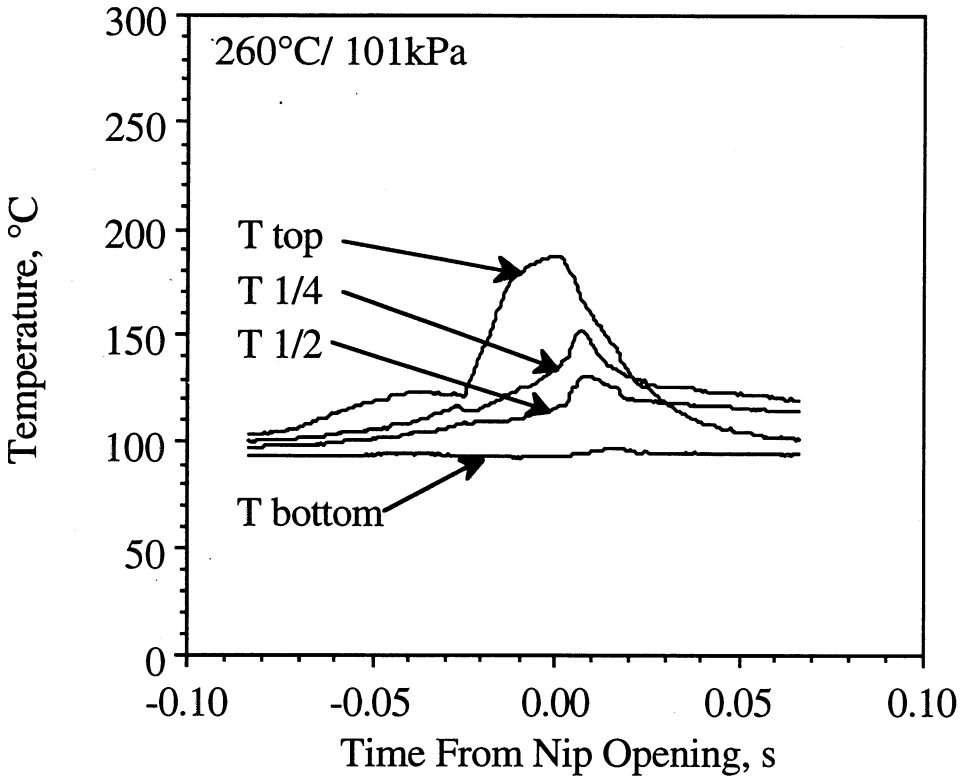

Figure 1. Measured Internal Sheet Temperatures as a Function of Time During Impulse Drying at a Press Surface Temperature of 260°C and a Nip Opening Pressure of 101 kPa (abs).

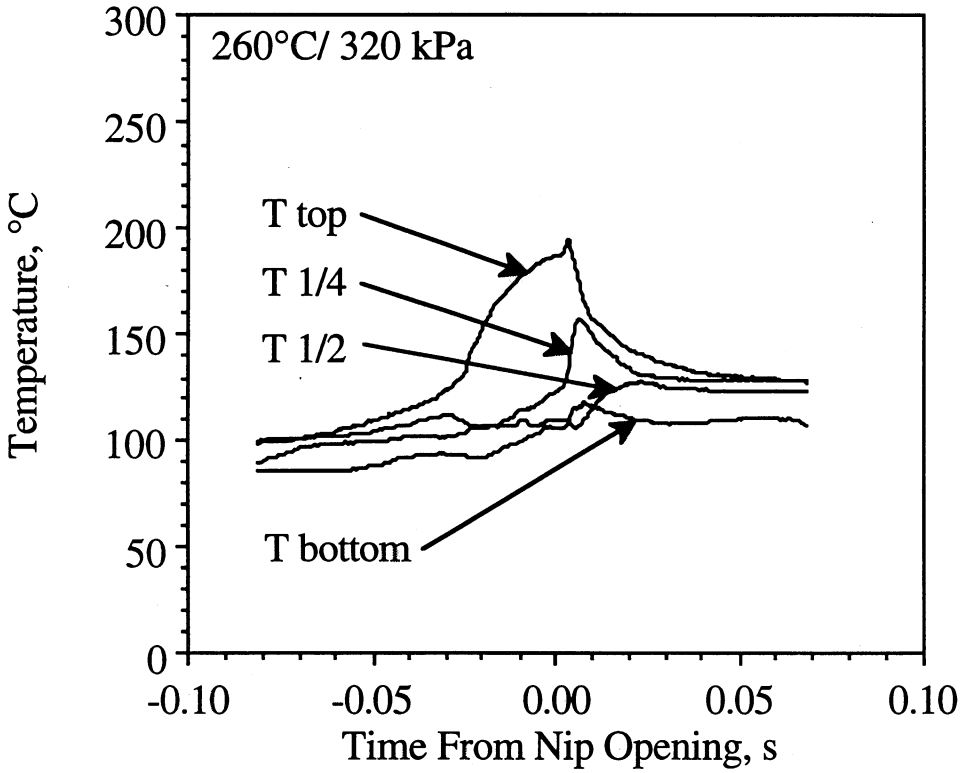

Figure 2. Measured Internal Sheet Temperatures as a Function of Time During Impulse Drying at a Press Surface Temperature of 260°C and a Nip Opening Pressure of 320 kPa (abs).

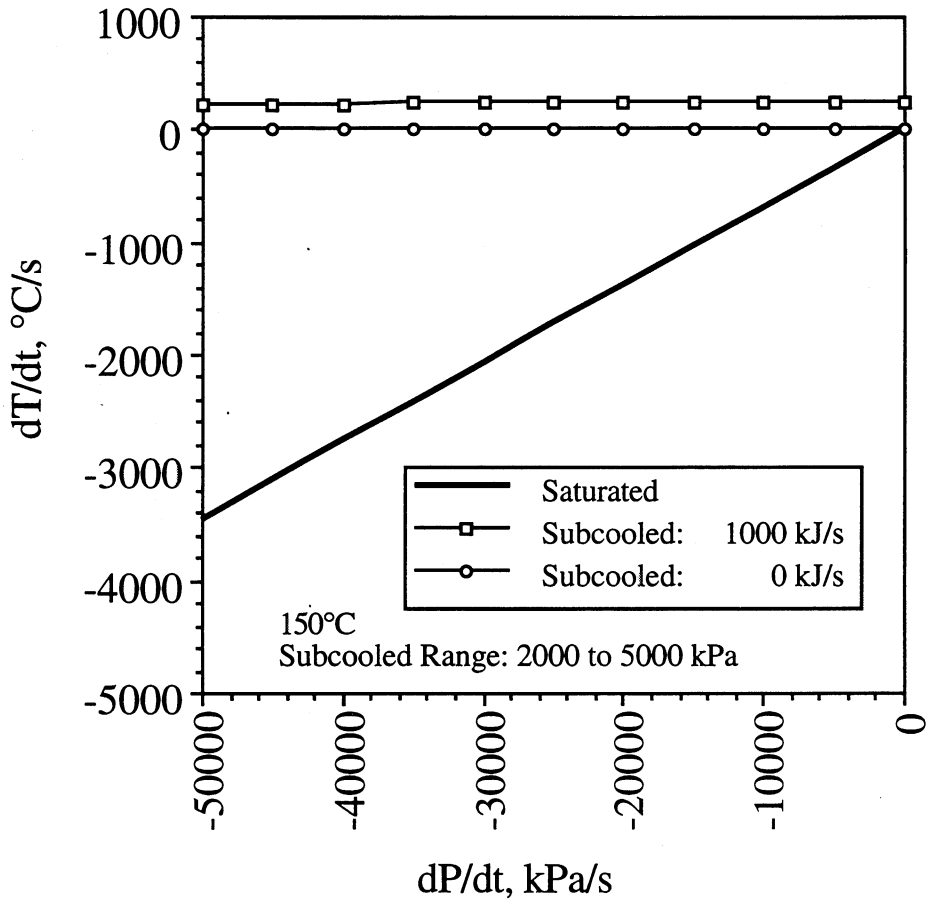

Figure 3. Calculated Rate of Temperature Change with Respect to Time, Assuming Subcooled Liquid as well as Saturated Mixture for Various Heat Transfer Rates and Depressurization Rates at a Temperature of 150°C.

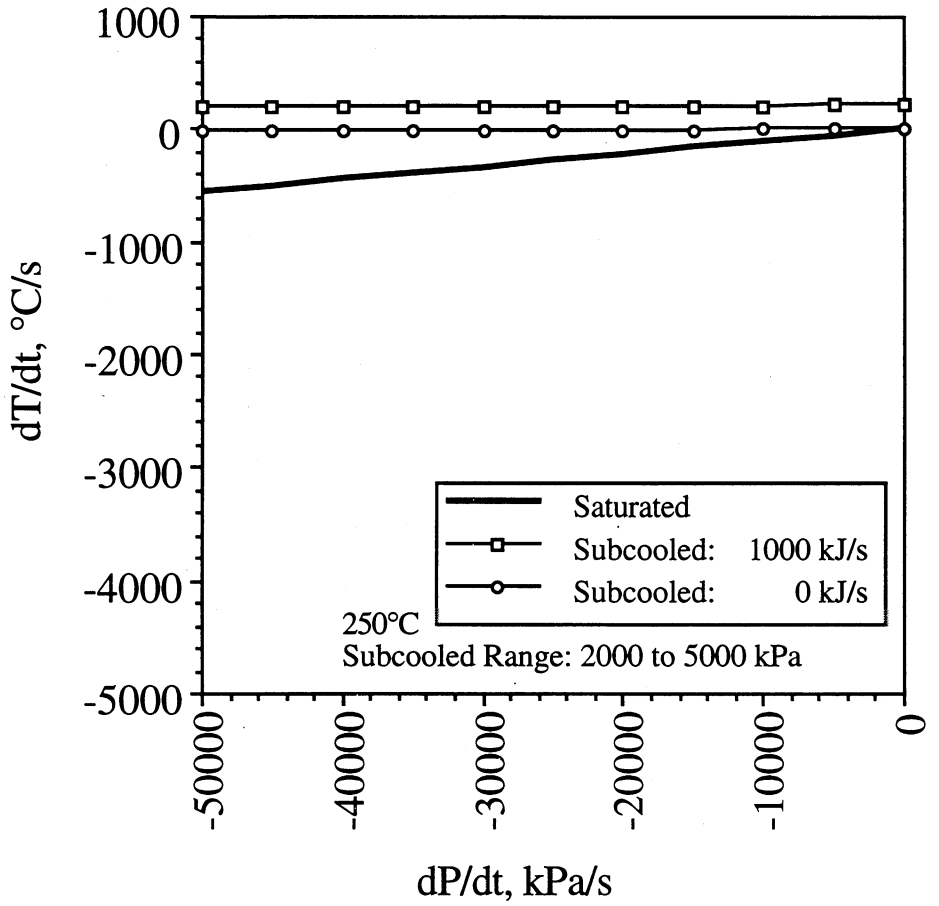

Figure 4. Calculated Rate of Temperature Change with Respect to Time, Assuming Subcooled Liquid as well as Saturated Mixture for Various Heat Transfer Rates and Depressurization Rates at a Temperature of 250°C.

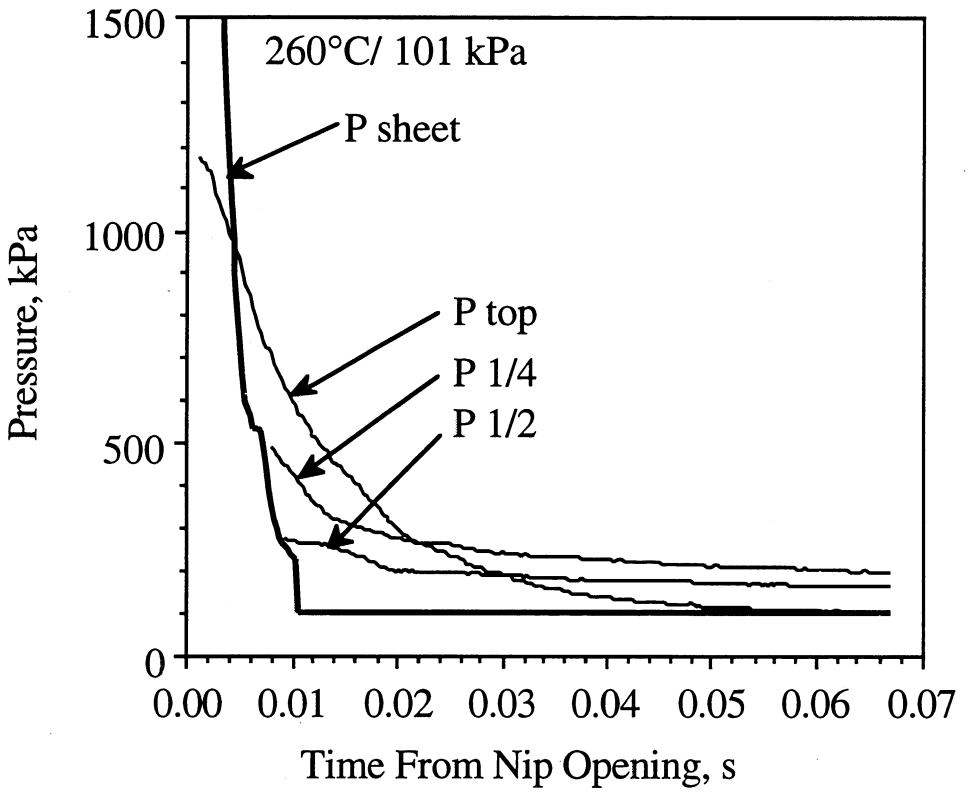

Figure 5. Internal and Sheet Pressure as a Function of Time From Nip Opening for Sheets Impulse Dryed at 260°C and an Ambient Pressure of 101 kPa (abs).

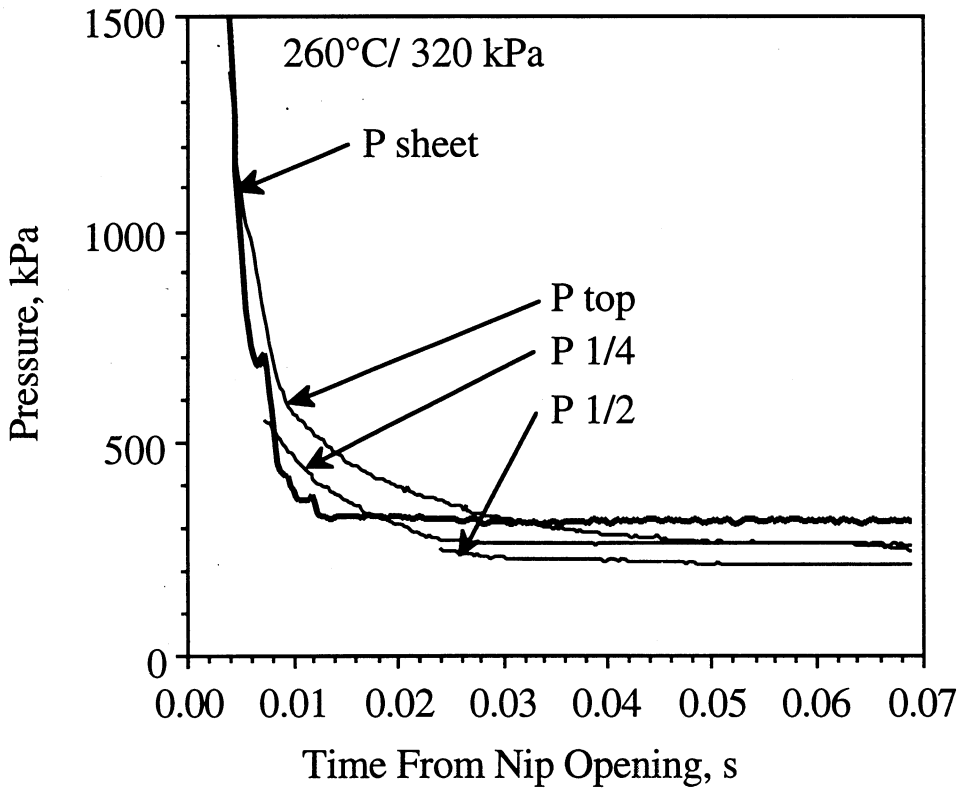

Figure 6. Internal and Sheet Pressure as a Function of Time From Nip Opening for Sheets Impulse Dryed at 260°C and an Ambient Pressure of 320 kPa (abs).

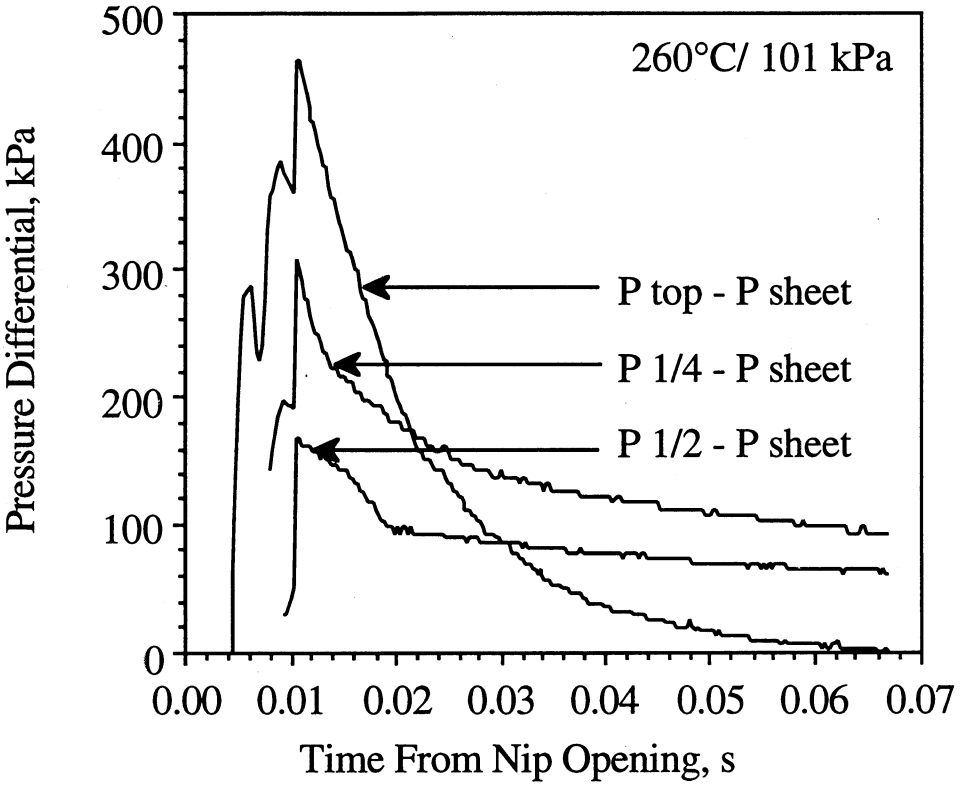

Figure 7. Pressure Differentials Between Various Internal Locations Within The Sheet and the Outside of the Sheet During Nip Opening of a Sheet Impulse Dryed at a Platen Surface Temperature of 260°C at an Ambient Pressure of 101 kPa (abs).

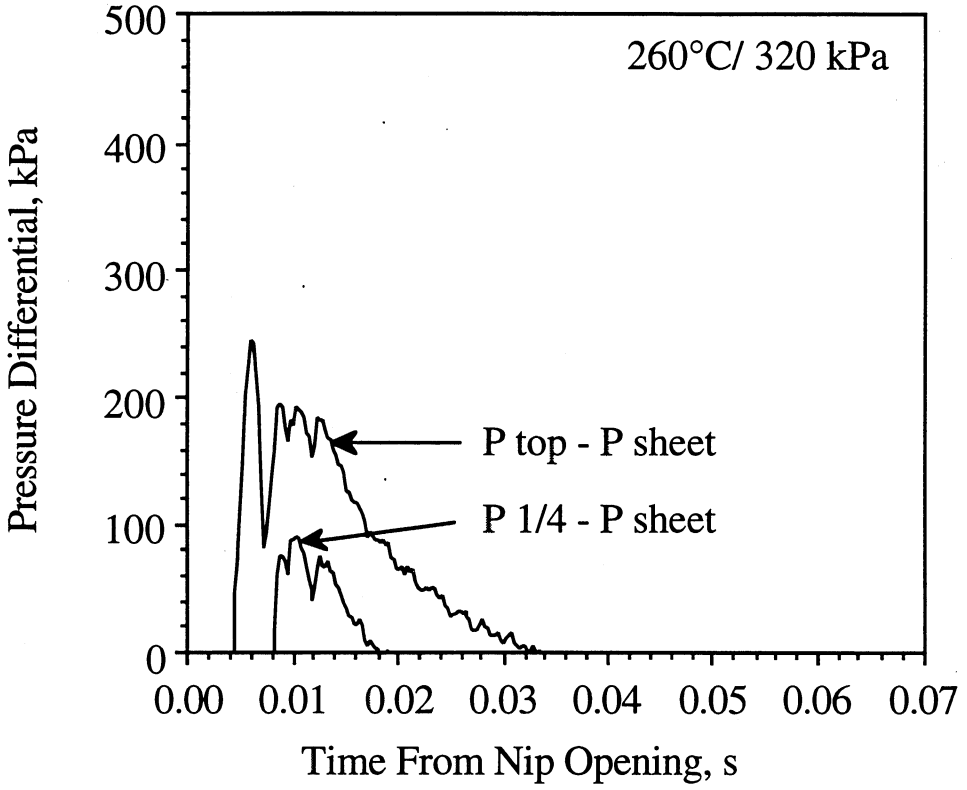

Figure 8. Pressure Differentials Between Various Internal Locations Within the Sheet and the Outside of the Sheet During Nip Opening of a Sheet Impulse Dryed at a Platen Surface Temperature of 260°C at an Ambient Pressure of 320 kPa (abs).

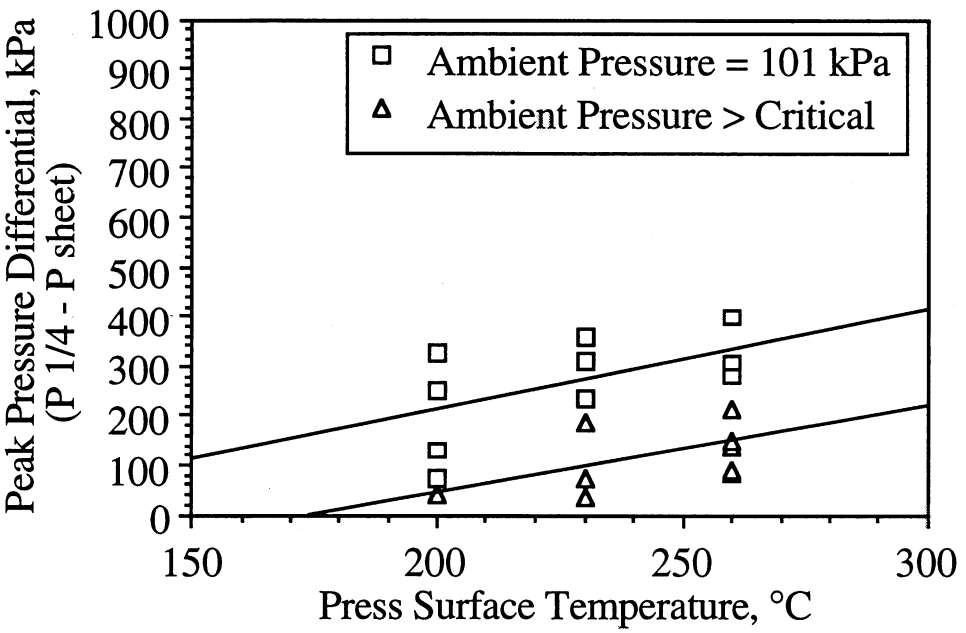

Figure 9. Peak Pressure Differential as a Function of Platen Surface Temperature as Measured at the "1/4" Position of the Sheet.

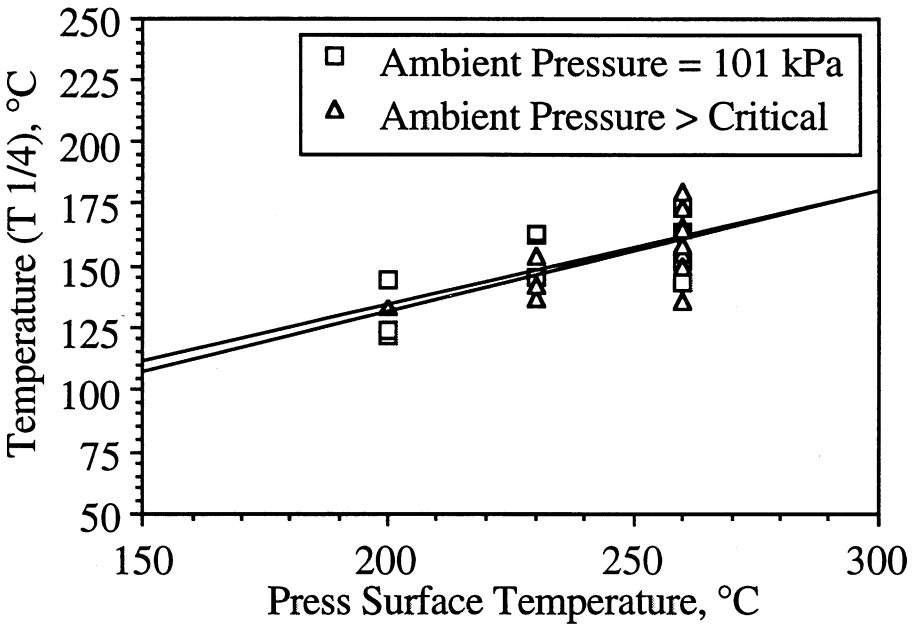

Figure 10. Peak InternalTemperature as a Function of Platen Surface Temperature as Measured at the "1/4" Position of the Sheet.

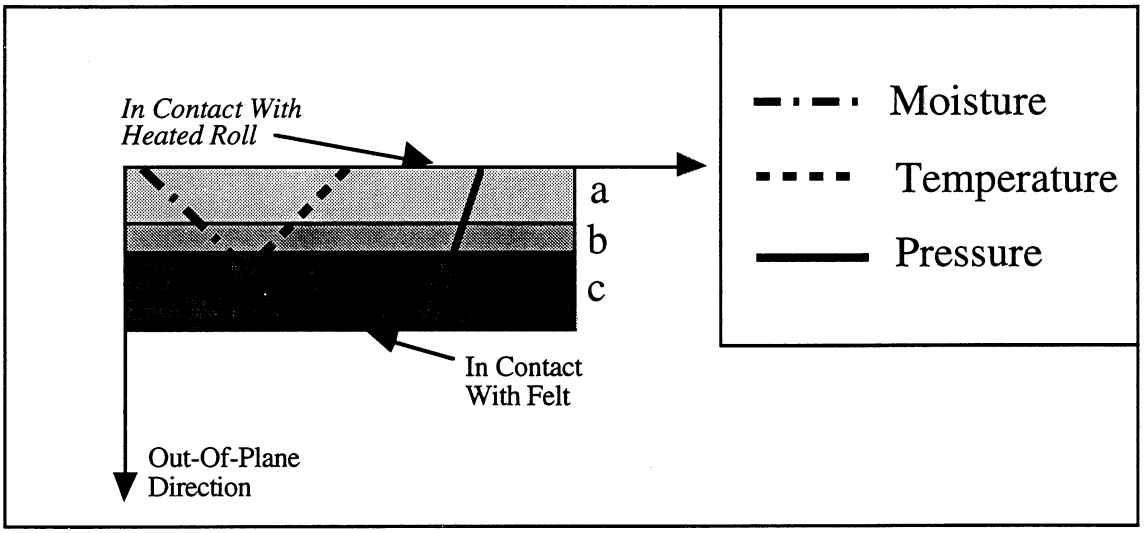

Figure 11. Conceptual Moisture and Temperature Profile Just Prior to the Nip Opening.

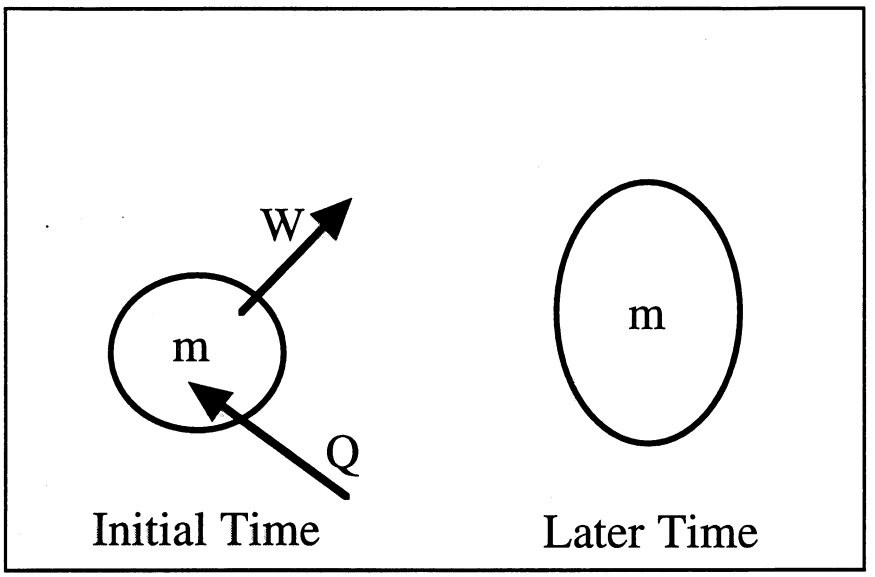

Figure 12. The Thermodynamic System.

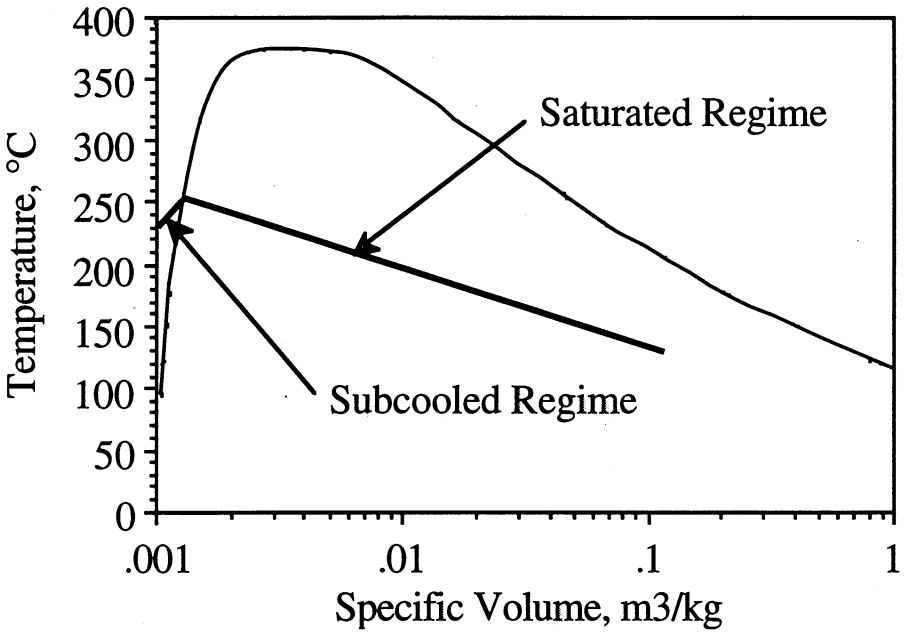

Figure 13. ***T-v*** Diagram Showing the Nip Opening Process.